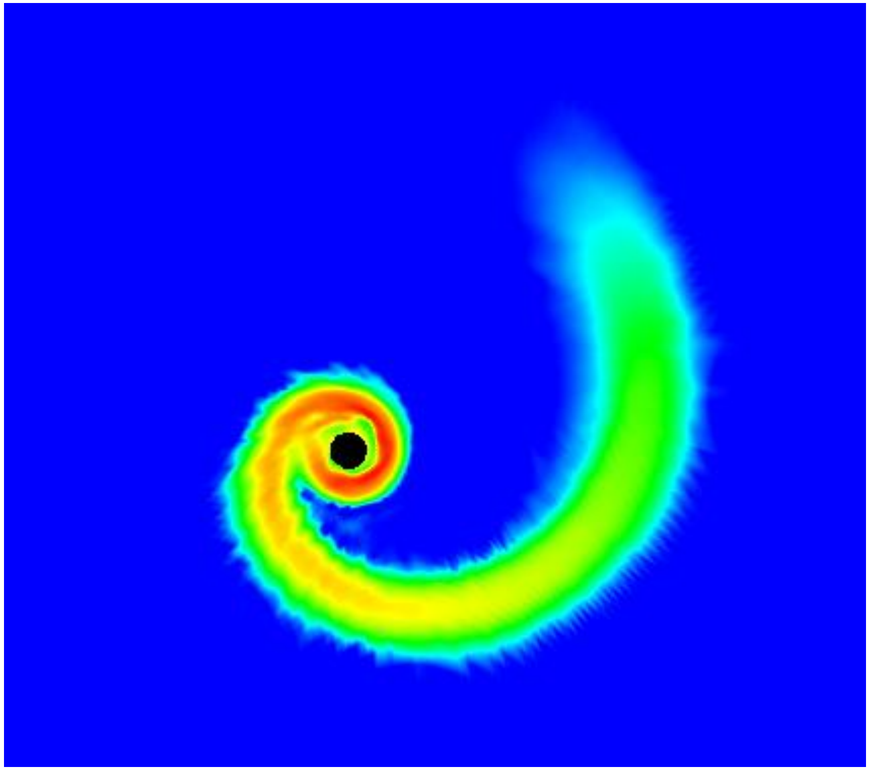
New steps toward realistic simulations of general black hole-neutron star mergers



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BHNS Binaries

- Merger rate: 10^{-6}-10^{-5}/Myr/MWEG (Pop. Synth.)
- AdvLIGO rate: 1-10/yr
- Short GRB engine? (need disk + clear region)
- r-process elements? (need unbounded ejecta)

A range of possible behaviors

- $M_{\mathrm{BH}} \gg M_{\mathrm{NS}}$
  - expect plunge @ ISCO, NS swallowed whole
- $M_{\mathrm{BH}} \sim \mathrm{few} \times M_{\mathrm{NS}}$
  - Disruption, mass transfer
  - Stable vs. unstable mass transfer
  - Disk? Ejected matter? Surviving core?

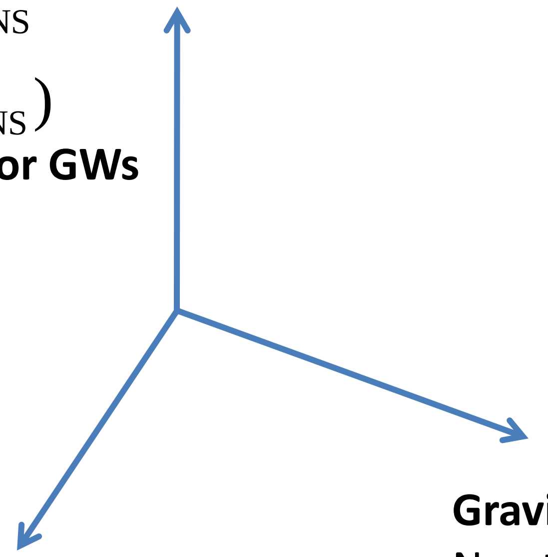
The challenge to Numerical Relativists

General Cases

$M_{\mathrm{BH}}, M_{\mathrm{NS}}$

$\vec{J}_{\mathrm{BH}}\ (,\ \vec{J}_{\mathrm{NS}})$

Need this for GWs



Gravity

Newtonian/P-W

PN/Conformal

GR

Need this to get GWs and GRBs right

Microphysics

EoS (Γ-law, nuclear theory)

Magnetic fields

Neutrino effects

Nuclear reactions

Need this for GRB models

Effects of mass ratio $q=M_{BH}/M_{NS}$

- For higher q, expect
  - Disruption closer to plunge
  - smaller disk, more BBH-like GWs
- Studied by Shibata *et al* (09), Etienne *et al* (08): $1 \leq q \leq 5$

Effects of BH spin $s=a_{BH}/M_{BH}$

- For higher aligned s, expect
  - Smaller ISCO → larger disk
  - Longer inspiral
- Studied by Etienne *et al* (08): s=-0.5,0,0.75 (aligned)
- High s → big $(10^{-1} M_{\odot})$ disk

The effect of NS Equation of State

- EoS affects both NS compaction and stability of mass transfer
- Lee (00,01) varied Γ from 5/3—3, Faber *et al* used Γ=1.5,2
- Janka *et al* (99) used L-S, Rosswog *et al* (04) used Shen
- In Newtonian gravity, disks much smaller for Shen than L-S
  - Rosswog *et al* (04)
- In Newtonian gravity, possibility of multiple mass transfers (MMT)
  - Lee (00), Rosswog *et al* (04)
  - Use of P-W potential (Rosswog 05, Ruffert & Janka (09)) or GR tends to remove MMT
- In GR, Shibata and Taniguchi (08) studied the effect of varying **compaction** for Γ=2 polytropes ($P=\kappa\rho^{\Gamma}$)
  - More compact star→ smaller disk, stronger GW signal

Our Cases

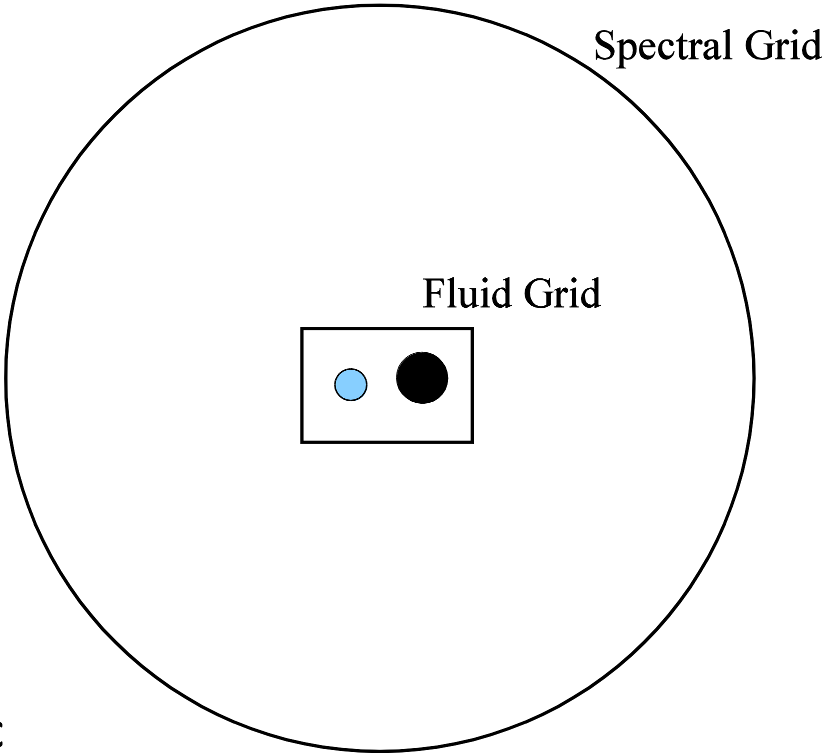
- Constants
  - $q=M_{BH}/M_{NS}=3$
  - $d(t=0)=7.5M$ (≥2 orbits of inspiral) + Eccentricity removal
- Spin variation
  - Fix $\Gamma=2$ EoS, $C=M_{NS}/R_{NS} = 0.15$
  - Vary $s=a_{BH}/M_{BH}=0, 0.5, 0.9$
- EoS variation
  - Fix s=0.5
  - 1) $\Gamma=2$, C=0.15
  - 2) $\Gamma=2.75$, C=0.15, 0.18
  - 3) Shen *et al* EoS, C=0.15

    advect Y_e (Shen-Adv) or impose β-equil (Shen-β)

    use full Shen table, or use $T=0$ table + $\Gamma=2$ thermal part

Our Code

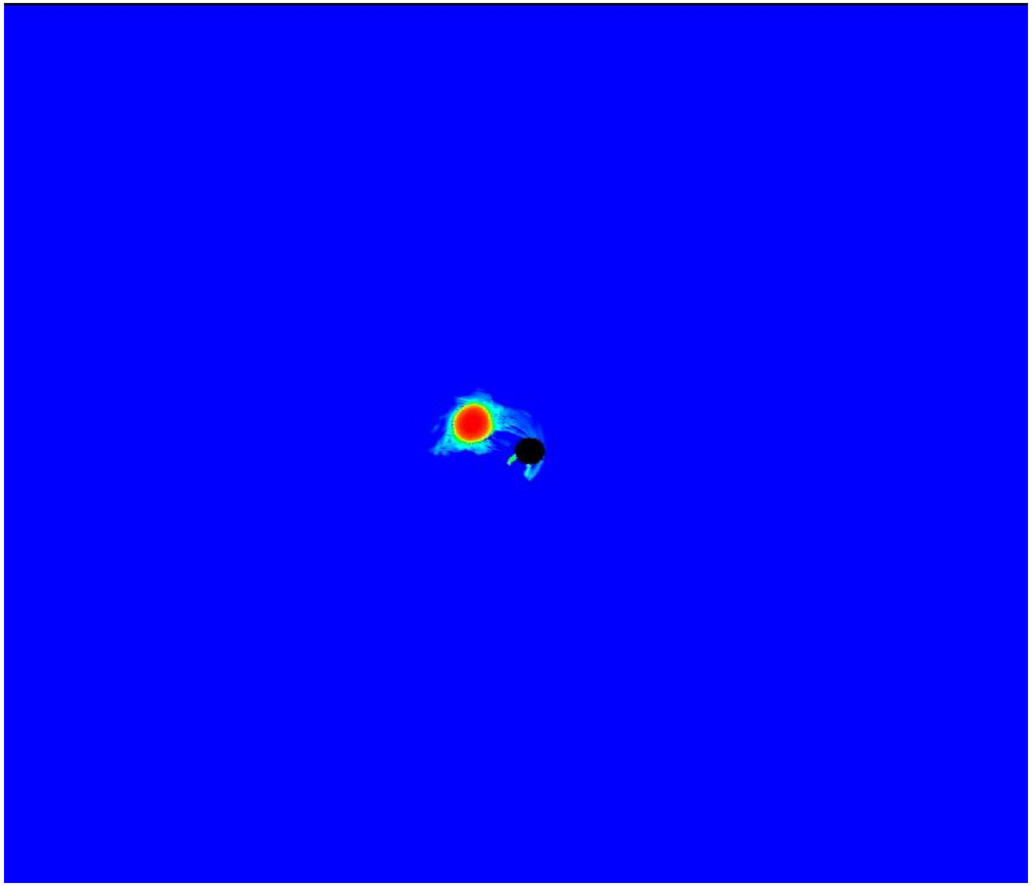
- Pseudospectral GR, GH formulations
- Shock-capturing FV hydro
- 2 grids, interpolation, automated remapping
- BH excision, comoving coords



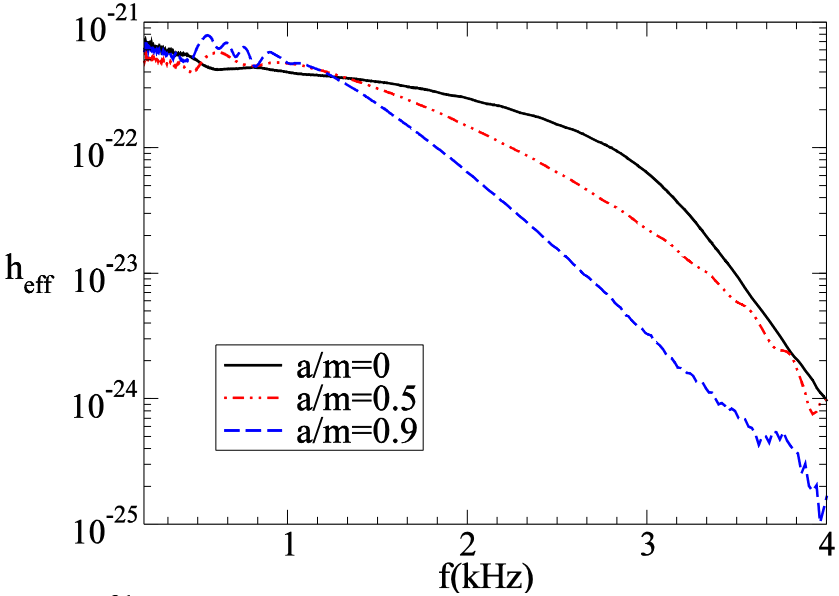
- New improvements:
  - $|C| \sim 10^{-4}$-10^{-3} (inspiral)
  - $|C| \sim 10^{-2}$ (merger)
- Inspiral: 10,000 CPU-h on 32 proc
- Merger: 20,000 CPU-h on 48 proc

Qualitative features of the mergers

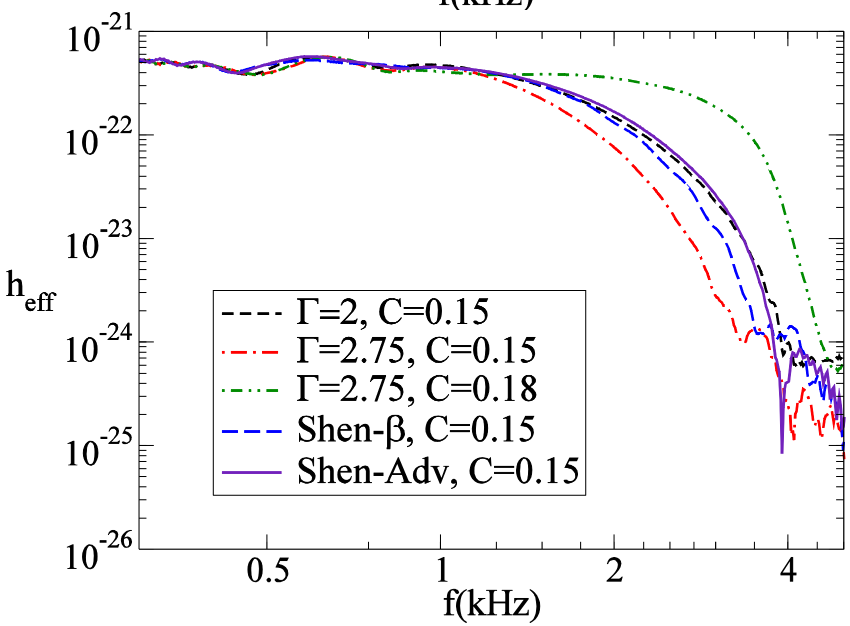
- Single disruption event
- Tidal tail, disk



The gravitational wave signatures

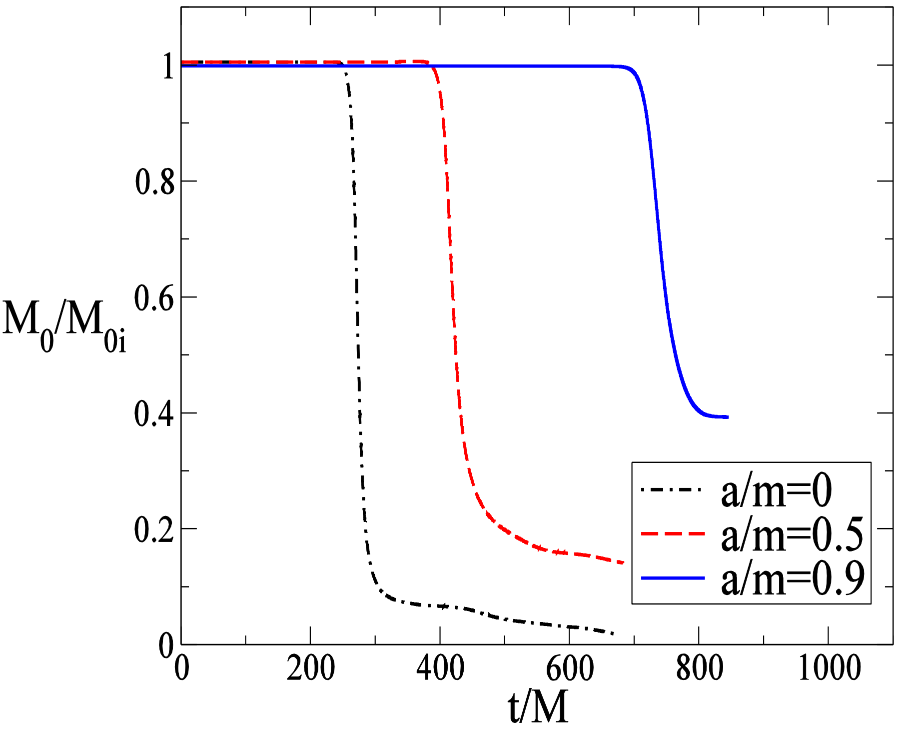


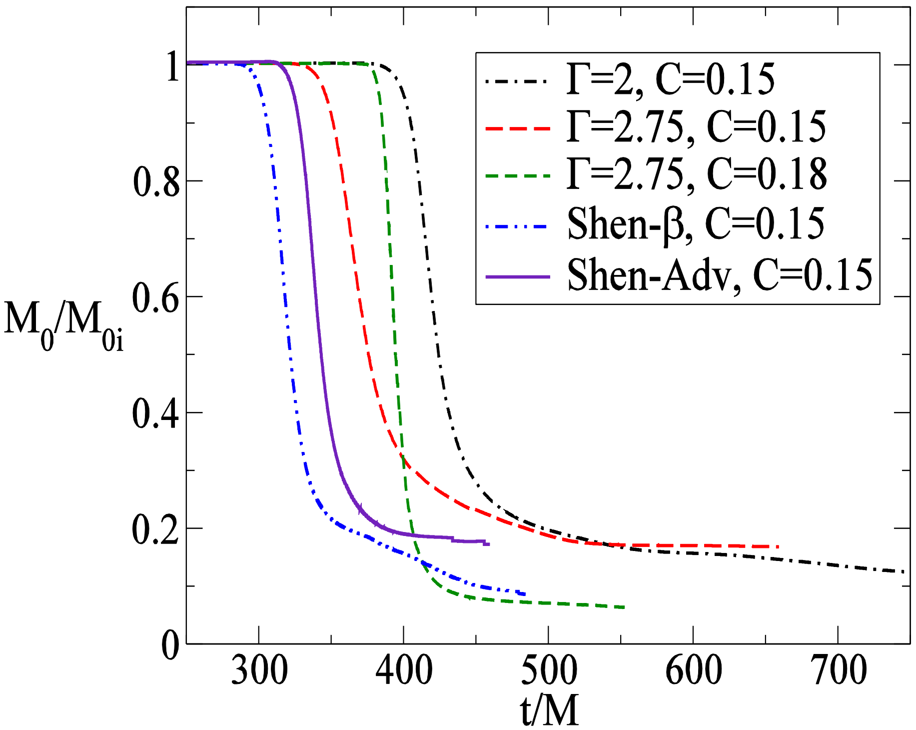
- Spin
  - Orbital hangup
  - Smear radius



- EoS
  - Large compaction effect
  - Smaller Γ, Y_e effects

The post-merger disks





Disk properties

- $\rho_{\rm max} \approx 5\times10^{12}\,{\rm g\,cm^{-3}}, \quad \delta\rho/\rho \approx 0.2$
- r~100km, H/r~0.15, $H_{\rm max}$=80km
- $\langle Y_e \rangle$~0.06 (Adv) ~0.2 (β)
- $\langle T \rangle \approx 3.5{\rm MeV},\; T_{\rm max} \approx 20{\rm MeV},\; \langle c_{\rm s} \rangle / \langle c_{\rm s}(T=0) \rangle \approx 1.7$
- $\ell \sim$ const, F_P/F_{cent}~10^{-2}

Final BH properties

- $M \approx 5.5 M_\odot$
- a/m: 0→0.56, 0.5→0.78, 0.9→0.93

What happens next?

- To the disk
  - MRI turbulence: $t_{acc} \sim 10^{-1}\text{s for } \alpha_{eff} \sim 10^{-1}$
  - ν-cooling: $\tau_\nu \sim 10^2,\ L_\nu \sim 10^{52}\,\text{erg s}^{-1},\ t_{cool} \sim \text{s}$
    - c.f. similar Newtonian disk: Setiawan, Ruffert, and Janka (2006)
- With simulations
  - GWs:
    - focus on inspiral+disruption
    - Need for general cases, i.e. nonaligned BH spin
    - Current microphysics is nearly adequate
  - GRBs:
    - Focus on merger
    - Need MHD, ν-transport, nuclear reactions